

Introduction

The release of SRTM images by NASA over the past two years year has been greeted by foreign Earth scientist's as "NASA's gift to the World". The goodwill that this has engendered in parts of Africa, India, Pakistan and Bangladesh, as scientists in those countries contemplated what many of them considered an unprovoked and unjustifiable US invasion of Iraq, cannot be underestimated.

We have used SRTM images from Africa and India and elsewhere to examine aspects of tectonism, geodynamics and tsunami and earthquake hazards. Highlights of this research are itemized in this final report. One difficulty that has arisen is , of course, that the funding for the science lead the availability of the data by more than a year, and as a result many of the findings are as yet unpublished.

1. Kilimanjaro region.

SRTM imagery were used to model relief in the vicinity of Kilimanjaro, a free standing volcano on the eastern flank of the African rift . The mass and footprint of Kilimanjaro are sufficient to depress the African continent to form a moat, and although this has been filled with lavas from the volcano, its approximate form can be followed from the intersection of Achaean rocks in water wells south of volcano. The collaborative project with Tony Watts in Oxford is as yet incomplete but results thus far indicate a depression of approximately 250 m with a radius extending to 50 km beyond the foot of the mountain. The volcanic edifice is thought to be less than 1 million years old and the data permit an estimate of continental flexural rigidity.

The IMAX movie Kilimanjaro used an SRTM image to demonstrate the separation of the Somali-plate from Africa.

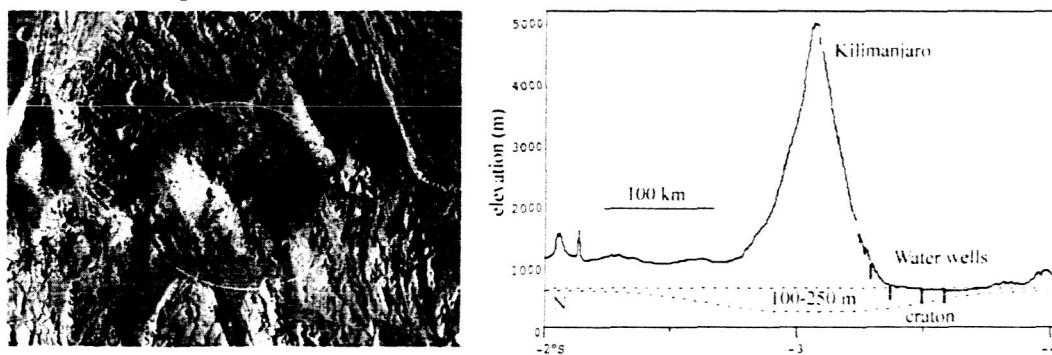


Fig. 1. SRTM image of Kilimanjaro and the approximate extent of its moat in map view and in profile. Water wells near Moshe have been used to constrain the upper surface of the bent plate.

2. Uplift and eastward tilt of the Andaman Islands

A study of tsunami records from the 1881 Andaman Island earthquake resulted in strong constraints on the mechanism of this event and on the possible uplift of the western coastlines of the Nicobar and Andaman islands during plate collision processes there (Ortiz and Bilham, 2003). The islands are off-limits for foreigners interested in field studies, but the SRTM imagery were of sufficient resolution to confirm and quantify that uplift of the westernmost islands of the archipelago does indeed occur.

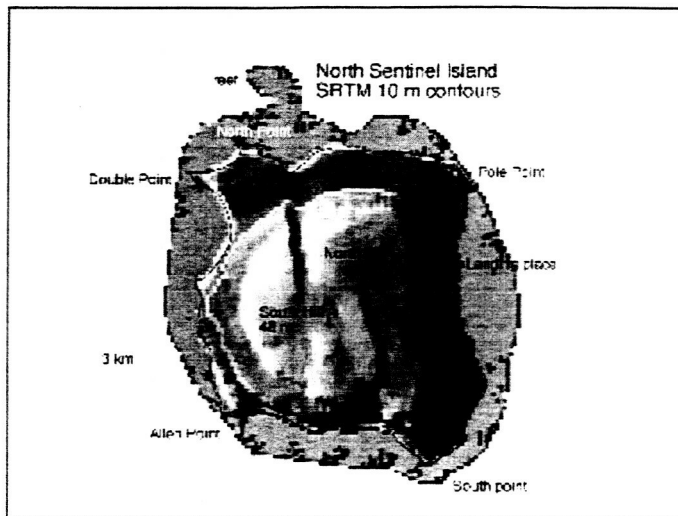


Figure 2 The image left shows North Sentinel island (3 km across), some 20 km to the west of Great Andaman island. The 10 m contours reveals a fringing reef surmounted by three marine terraces. The terraces are assumed to represent great earthquakes that occurred in the past several thousand years on the plate boundary. Preliminary investigations by CP Rajendran report uplift of the west Nicobars in the same sense.

3. Allah Bund earthquake 1819 and the Bhuj event of 2001

The 2001 Bhuj earthquake occurred approximately 150 km east of the 1819 Allah Bund earthquake of 1819. Attempts to undertake InSAR analysis of the 2001 earthquake were thwarted by the absence of good imagery in the pre-seismic and co-seismic STRM data. However, some success had been reported in forming scenes that show fringes. We undertook a number of analysis to determine whether the SRTM imagery could confirm reports of uplift of 3 m in 1819. These were inconclusive because the early data contained acquisition artifacts that still remain to some degree in more recent data. However, it would seem that the elevation of the Allah Bund may have undergone erosion and frontal retreat caused by the fetch of Lake Sindri.

In contrast to the absence of strong vertical constraints for the two earthquakes we have made some progress in identifying the probable extent of the 1819 causal fault. This may have extended much further to the west than thought previously, and there is some evidence to suggest that the fault is the surface manifestation of a structural feature that crosses the Indus towards Karachi.

We note that Lake Sindri is the easternmost of two depressions, one of which is in Pakistan. The northern edge of this western basin (thick dashed line) extends across to the Indus to where it may have perturbed the sinuosity of the Indus as it passes through its delta. (see region between black lines). The consequences of this feature extending

toward Karachi, is of course, that earthquakes exceeding $M_w=7.6$ could in fact occur quite close to Pakistan's largest southern city.

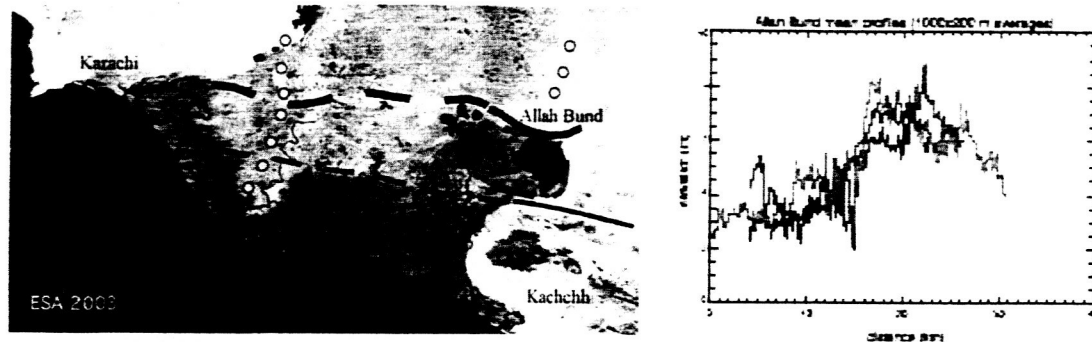


Fig. 3. SRTM elevation profiles across the Allah Bund (right) do not provide precise constraints on the morphology of the surface in the hanging wall of the supposed causal fault to the 1819 earthquake (collaborative investigations with Eric Fielding). We assume that the southernmost 6-m-high edge of the bund may have been eroded in the past century during monsoon flooding of the Rann of Kachchh.



Figure 4. Earthquakes in the Indus delta and Rann of Kachchh may have resulted in subtle features discernable on SRTM imagery. Earthquakes in 1845 and 1856 were never investigated in detail and what little data have survived provide a historically confusing picture. Conjectural locations for these events, which may have exceeded $M=7$, are depicted as topographic scarps contiguous with the 1819 Allah Bund. The scarp near Karachi is less clear but could be associated with the disappearance of Debil after an earthquake in 1668.

4. Frontal thrusts Himalaya

Regions of uplift identified in leveling profiles across the frontal thrust of the Himalaya have been variously interpreted as creep on the frontal thrusts and as strain linked to convergence processes in the Greater Himalaya. SRTM imagery has permitted us to gain some additional insight into the processes that may be responsible for local uplift in the frontal Himalaya. The SRTM imagery show clearly that subsidence in the Kathmandu

valley is confined to the ancient valley sediments there. Regions of uplift in the Mahabharat mountains west and south of Kathmandu, and in the Siwalik Hills, near the frontal ranges of the Himalaya, if they are not artifacts of leveling caused by the along-line slopes traversed by these surveys, are quite probably processes caused by subsurface creep. However, there is no clear association of similar amplitudes of uplift in the region most unlikely to be affected by errors in leveling data, between Amlekganj and Hetauda in the Nepal Terai. The curious absence of surface features south of the main frontal thrusts, and south of the region of surface incision caused by activity in this region, is of interest. It suggests that incipient thrusting below the Terai may be occurring. Blind thrusts have been mapped in the region by seismic reflection surveys. If these systems are active, their slip must be driven by potential energy in the Himalayan forelands since the main decollement is inactive.

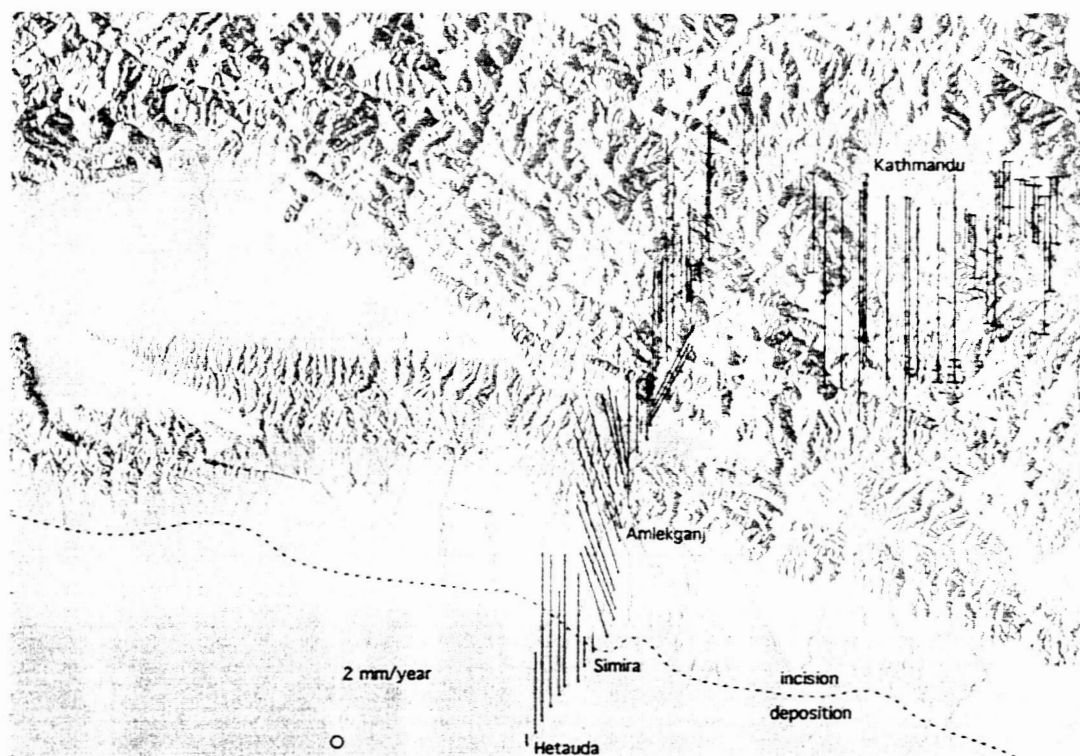


Figure 5 Leveling data reveal uplift near Amlekganj and west of the Kathmandu valley in the Mahabharat range. They also suggest that uplift presently occurs south of the main frontal thrusts associated with creep on blind thrusts beneath the Terai. The lines indicating uplift of specific bench marks have been tilted to prevent overlap.

5. Salt Range offset of River Indus

As part of an NSF project we installed a large number of GPS points across the southern edge of the Shillong Plateau to determine its rate of slip. The tectonic target in this case was the question of whether the salt range slips aseismically, or only at times of

earthquakes. We used the SRTM data to examine features that have been offset by this process. The data are sufficiently high resolution to identify ancient mound cities bordering the Indus, but the most remarkable observation is the offset of the Indus itself. We plan to inspect the region of the 5 km offset in a future visit in order to search for materials that might provide an indication of the time of the abandonment of a straight course through the range. The development of the Salt Range may have occurred through slow aseismic creep or through episodic events and it is possible that shifts in the course of the rivers crossing the range may hold clues to distinguish these two end models.



Figure 6 Offset of the river Indus by slip of the western edge of the Salt Range. We seek to learn whether the Potwar plateau is offset in large earthquakes or by steady creep.

6. Shillong Plateau

Until quite recently the great Assam earthquake of 1897 was thought to have occurred on a shallow, north-dipping thrust fault beneath the Shillong Plateau. Geodetic data from 1860-1936, however, suggest that the plateau is bounded by steep reverse faults that dip towards each other, and that the 1897 earthquake resulted in slip on the northern boundary fault, the Oldham fault. SRTM imagery sheds new light on the processes that may have lead to the development of the plateau as a "pop-up" feature, since they show that the plateau is fronted to its south by a large monocline. The present plateau surface, though heavily dissected, follows the fold axis.

Elastic models that match the folded, uneroded surface require a crustal scale decollement with a ramp terminating close to the base of the sediments fronting the edge of the plateau. In this scenario the decollement may have ramped initially against the oceanic plate, and once developed, would have encouraged failure through an antithetic fault in the angle bisected by the decollement and ramp. Models show that Coulomb failure is optimized for a fault steeper than that anticipated from reverse faulting in a slab under horizontal compression. Thus a 45° ramp representing the Dauki fault engenders a 50° dipping synthetic Oldham fault, a possible mechanism for avoiding supra-pressures whose presence has been invoked by Rick Sibson to explain steep reverse faulting.

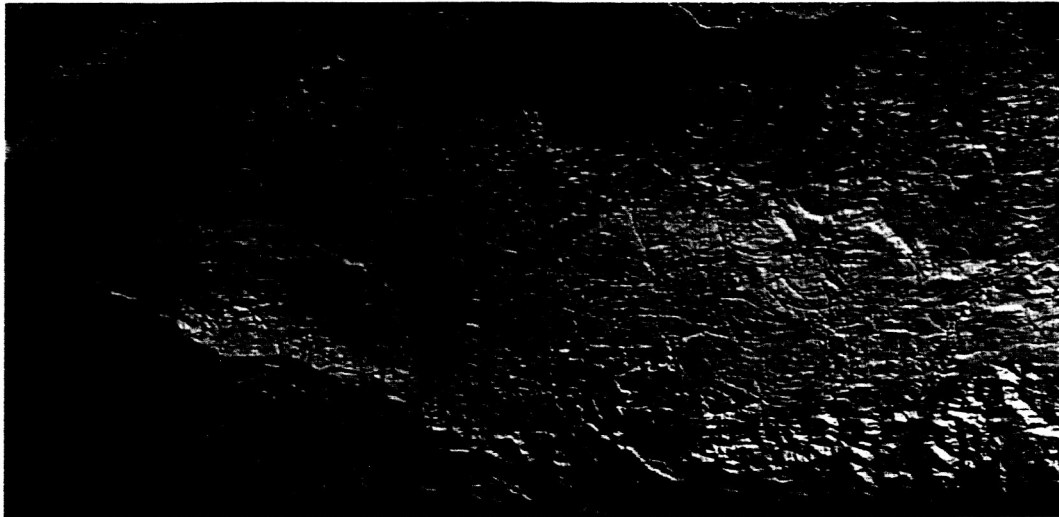


Figure 7 A 300-km-long east-west view of the Shillong Plateau shows a monocline on its southern surface, beneath which the Dauki fault is active. The northern boundary fault, the Oldham fault, terminates 9 km below the surface but its surface projection would emerge near the ESE trending scarp along its northern edge.

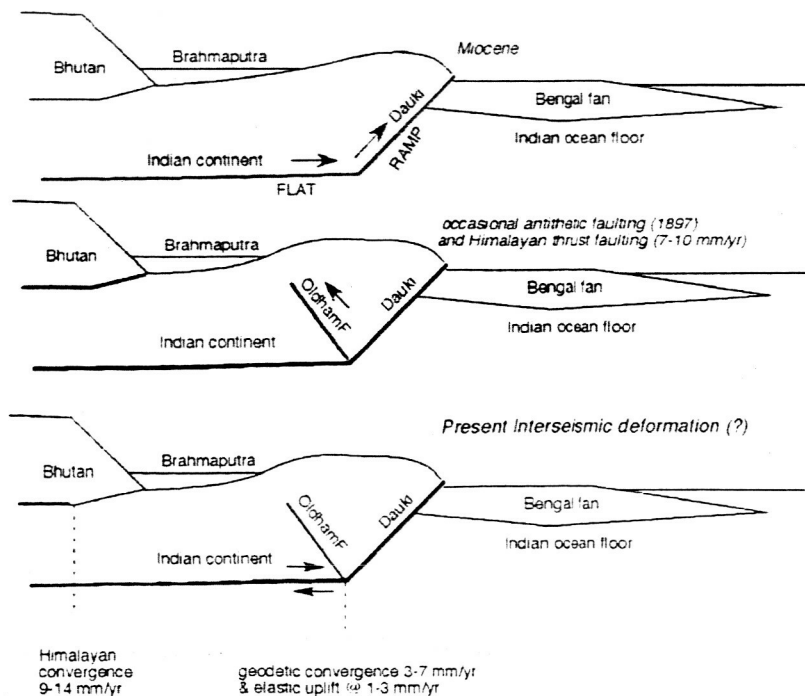


Fig. 8 shows the development of the Shillong Plateau since the Miocene. Coulomb models indicate that the Oldham fault would be initiated after slip on the ramp/flat system that may initially have developed at the edge of the continental and oceanic Indian plate. The mechanism may be what is occurring presently in the Kachchh region.

The cartoon (Figure 8) shows how we envisage this process to have developed since the Miocene. The Dauki fault is first active, but after a few km of slip on the ramp, Coulomb failure is encouraged along the Oldham fault, which causes uplift of the northern edge of the plateau. Thereafter both faults have participated alternately in uplift of the southern and northern plateau to its present elevation of 1.6 km. Interseismic creep on the inferred flat underlying the Brahmaputra valley would result in a broad region of uplift and convergence centered on the Shillong plateau (lowest panel). In collaboration with Indian scientists we have installed a number of GPS points to monitor this strain-field, to test for its existence.

7. Flexure of India and erosional processes on the flexural bulge.

The northern edge of the Indian plate is depressed some 40 km by the weight of southern Tibet. As a result it is subjected to flexural forces that raise central India approximately half a km above its unstressed level, and depress a region to its south by some 40 m. These flexural forces impose a stress system in the sub-continent that is responsible for mid-continent earthquakes, and for earthquakes beneath the main decollement of the Himalaya.

An important new challenge is to determine the precise elevation and location of the bulge. This so-called "hidden range" first described by the Survey of India in the 1920's from its gravity signature. Its peak was referred to as a crest-line and its depressed regions were termed trough lines. The apparently insignificant depression with a N-S wavelength of more than 500 km south of the forebulge, almost doubles stresses in the upper part of the Indian plate. These increased surface stresses (near Latur), and their transfer to the base of the Indian plate near the crest of the bulge (near Jabalpur) are the underlying physical reason for earthquakes in India.

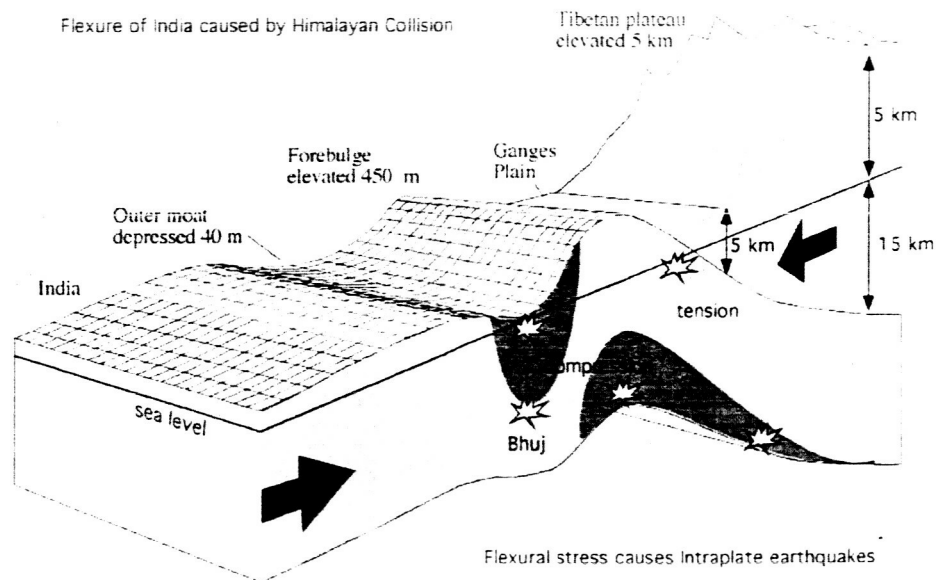


Figure 9. Approximate geometry and consequences of the flexural bulge in central India.

The gravity field over India provides a crucial constraint of India's flexural geometry. A recent intriguing hypothesis is that India's northward progress is weakly retarded prior to sequences of earthquakes in the Himalaya causing increased stress in the Indian craton. If such stress changes prevail they may be reflected by increased buckling in India prior to Himalayan $M > 8$ earthquakes, with a corresponding reduction in flexural amplitude in subsequent centuries. The resulting gravitational changes may be sufficiently large to be monitored by potential field satellites such as GRACE.

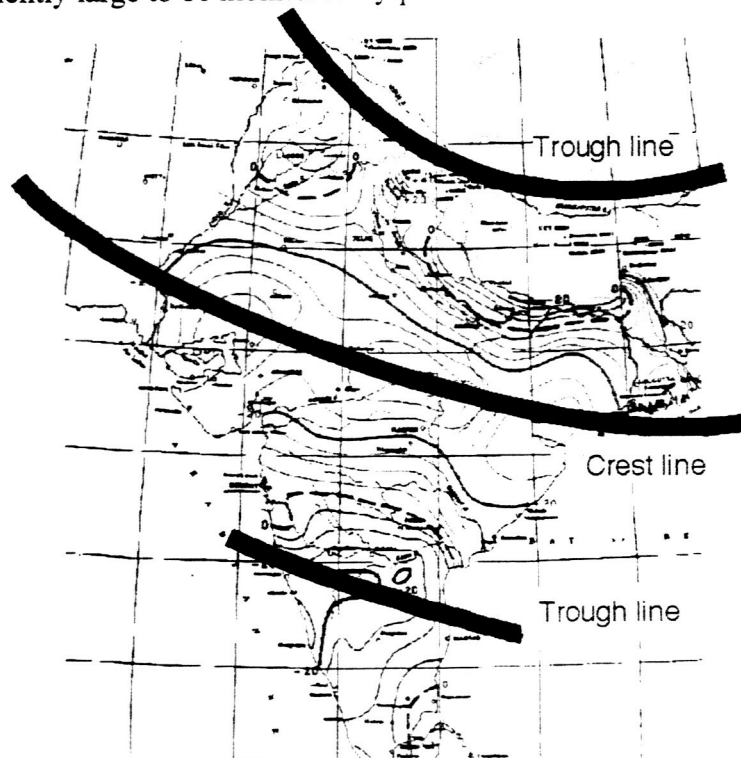


Fig 10 Survey of India gravity field with India's outer rise –the "hidden range" –labeled *Crest line*, and the Gangetic fore-deep and the outer flexural trough each labeled *Trough line* (Glennie, 1932). This figure by a contemporary of Wegener predates plate tectonics by 35 years.

SRTM methods have importance in confirming the precise geometry of this stress system. India streams sluggishly northward through flexural troughs and bulges generating slow strain changes that over millennia, and when combined with stress changes caused by erosion, deposition, topography, reservoir-construction or nearby earthquakes, cause local rupture of the Indian craton. Stresses cannot be sensed remotely but their resulting strain and elevation changes influence the development of topography, river networks and coastal erosion.

In a recent analysis (Bilham et al., 2003) we searched for an erosion-base within the forebulge. These data indicate a width of 650 km and an elevation 450 m. We plan a more careful analysis using SRTM measures of river valley levels in central India to

refine this estimate, and the possible effects of sustained elevation and growth over the past 20 million years.

8. Chaman fault system and Baluchistan

We have initiated a series of studies of India's western plate boundary with Asia and have been using SRTM data to constrain deformation associated with known historical earthquakes and with possible creep on the Chaman fault system using InSAR Methods.

9. Tsunami hazards Eastern India

We have examined the interaction of coastal populations characterized by night-light imagery with tsunamis generated along the Andaman plate boundary. We have used SRTM elevations to determine maximum areas of coastal run-up near Madras.

Publications

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